Manufacture of an Integrated Three-Dimensional Structure Nozzle Plate Using Microinjection Molding for a 1200-dpi Inkjet Printhead

Sheng-Chih Shen, Min-Wen Wang, and Chung-Jui Lee

Abstract*—This paper presents an integrated microtechnology for the fabrication of a 3-D structure nozzle plate for a 1200-dots-per-inch (dpi) inkjet printhead. The 3-D structure nozzle plate contains a fluidic channel, nozzle chamber, and 432 conical nozzles whose taper angle is about 9°–11° to vertical. When the integrated 3-D structure nozzle plate is packaged onto the printhead, there is no need for alignment between the nozzle and the ink chamber, as there is when conventional production methods are employed. Therefore, misalignment of the nozzle and ink chamber is avoided, thereby reducing the cost by up to 50%, as well as greatly improving the print quality. This paper demonstrated the integration of excimer laser technology and microinjection molding to fabricate a 3-D structure nozzle plate. Excimer laser technology was used to create the high aspect ratio pattern with a tapered angle structure, and then, high-hardness Ni–Co alloy microelectroforming technology was used to achieve micromold insertion of the nozzle plate. In the microinjection molding, a variotherm control system was utilized for rapid heating to the mold temperature, which must be close to the glass temperature to ensure a good replication of the nozzle plate. The experiment resulted in the fabrication of a 3-D structure nozzle plate 2.7 mm in width and 10.8 mm in length. The total thickness was not more than 80 ± 2 μm (ink channels, nozzle chamber, and nozzle plate), and the diameter and pitch of the nozzle holes were 25 ± 2 μm for the outlet, 43 ± 2 μm for the inlet, 84 ± 2 μm in pitch, and 30 ± 2 μm for the ink channel. Using this 3-D structure nozzle plate improved the competitiveness of the inkjet printhead. We have demonstrated the manufacture of the main parts of the 3-D structure nozzle plate for a 1200-dpi printhead; the aforementioned fabrication process yields satisfactory results and can be applied to commercial production. [2008-0079]

***Index Terms*—Excimer laser, Lithographie Galvanoformung Abformung (LIGA), microelectroforming, microelectromechanical systems, microinjection molding, nozzle plate.**

I. Introduction

THE DEVELOPMENT of injection molding began more than 30 years ago, and the micromolding of thermoplastic polymers is now one of the most promising fabrication technologies for microdevices [1]. Microinjection molding can be described as a method of fabrication of microstructures or components with volumes within the range of millimeter scale, and the 3-D structure nozzle plate conforms to this description. Currently, the inkjet printer is of low manufacture cost with a comparatively good print quality. The market share of the printhead has grown dramatically over the few past years due to its advantages of low machining cost, high quality of color printing, and high resolution [2], resulting in a rapid expansion of this technology in recent years. The 3-D structure nozzle plate avoids the generally used multilayer design in which the first layer includes the electronic circuit and the heaters; the second layer contains the fluidic parts such as channels, runner, and chambers; and the third layer consists of the nozzle plate with laser-drilled nozzles [3]. Additional advantages of the 3-D structure nozzle plate are the reduction of processing steps and the need for only one assembling step. The micro nozzle plate is the most important part of the printhead and influences droplet formation and stability [4]. Therefore, the fabrication of printheads could be made cheaper and more reliable as compared with conventional printheads. However, how to reduce the production cost is an important task, and Lithographie Galvanoformung Abformung (LIGA)-like technology and high injection speeds, which could potentially be used in the mass production of microstructures, provide a suitable solution [5]. In addition, the micro nozzle plate can also be applied in other fields, for example, rapid expansion of a supercritical solution (RESS) [6], thin-film transistor (TFT)–liquid crystal display cooler filters [7], organic TFTs [7], organic memory [7], printed circuit board (PCB) printing [8], deoxyribunucleic-acid printing [9], accelerating chemical reactions [9], direct-patterned crystalline films [10], vapor production, drug delivery, and micronebulizers [11].

At present, three kinds of technology are generally used to fabricate the micro nozzle plate: 1) Microelectrical discharge technology. All traditional nozzle plates are fabricated by this technology; however, it is difficult to fabricate the micro nozzle plates required for high-resolution and high-density nozzle holes by this method; 2) microelectroforming technology. In this method, photolithography technology is used to pattern the nozzle plates, and then, a nickel nozzle plate with a tapered cave shape is fabricated by the method of transforming shrinkage. This technology uses the photoresist method to pattern the nozzle holes, and the distance between each nozzle hole has a limit. However, electroforming technology does not have an acceptable repeatability, particularly for high-resolution nozzle

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TABLE I
COMPARISON OF FABRICATION TECHNOLOGIES FOR NOZZLE PLATES

Technology	Electroforming	Laser ablation	Micro-injection molding
Nozzle Precision	±2μm~±3μm	±1μm	±2μm
Nozzle unity	Low	Middle	High
Pitch between the nozzle ≤ 85 μm	NA	Yes	Yes
With ink channel	NA	NA	Yes
Nozzle plate with taper angle	25°~35°	9°~15°	9°~11°
Cost	Middle	High	Low
Reference	[22]	[23]	

plates [when the resolution is greater than 600 dots per inch (dpi)]; and 3) excimer laser machining technology. This technology uses a pulsed beam to create micro nozzle holes with diameters in the range of 10–50 μm; however, the high cost of a single machine, lack of batch processing capability, low throughput, and low yield are the greatest drawbacks. The light source characteristics can, however, be used to pattern the high aspect ratio and micromold insert with the geometric structure of a tapered angle, and this is a perfect practical technology for producing a variety of microstructures. The photolithography process belongs to surface micromachining method in which a UV light penetrates vertically through the photomask and transfers the photoenergy into the photoresist. The process can only divide into energy-absorption and non-energy-absorption areas. Therefore, only vertical structures rather than the taper-angled patterns can be obtained by the photolithography process. In addition, excimer laser technology can be used for bulk micromachining; it can achieve a taper-angled pattern by controlling the laser parameter, such as energy density, focal size, frequency, and pulse number, as well as can perform multilayer, repeat, and complicated processes on the object.

In recent years, a number of technologies for polymeric microstructure replication have been proposed, including the LIGA process [12], [13], hot embossing [14], [15], and injection molding [16]–[19]. However, in the LIGA process, lithography using a synchrotron orbital radiation X-ray, and an X-ray masks is expensive; hence, in view of the cost, the LIGA process is only suitable for high aspect ratio components and complex structures In the hot embossing process, rapid expansion of trapped air results in viscous patterns, and local inhomogeneities in embossing pressure cause surface undulations, increasing the cycle time. Therefore, hot embossing is not suitable for the mass production of 3-D structure nozzle plates. Microinjection-molding technology not only has a short cycle time but also has the advantages of low cost, high precision, and wide material selectivity for mass production [20]. Chen and Lan [21] have successfully used microinjection-molding technology for ceramic microstructures. Table I shows a comparison of fabrication technologies for nozzle plates. The high-density unity geometry structure can allow for better pixel density and faster print times for speedy photographlike images; thus, the micro nozzle plate is a key part of the inkjet printhead. Traditional electroforming technology cannot satisfy the demand for high-quality color images and low machine cost; excimer laser drilling technology can satisfy the high-quality color image requirements; however, the machining cost is high, and the yield rate is low. Therefore, this paper presents an integrated microtechnology that uses excimer laser technology, high-hardness Ni–Co alloy microelectroforming technology, and microinjection-molding technology to fabricate a low-cost 3-D structure nozzle plate with a high-quality printing ability.

II. Mold Insert of the 3-D Nozzle Plate With Taper Angle

A. *Excimer Laser Machining*

The lithography process of the mold insert of a 3-D structure nozzle plate uses excimer laser technology to fabricate the cone-shaped nozzle. An Exitech 8000 excimer laser was used in this paper; this excimer laser system consisted in the main of a short-pulse Lambda Physik COMPEX-110 excimer laser source and an aerotech positioning system. The specifications of the excimer laser were as follows: wavelength, 248 nm; maximum pulse energy, 400 mJ; pulse duration, 25 ns; and maximum pulse repetition rate, 100 Hz. The focused spot size of the laser beam was 0.25×0.25 cm^2. The photomask projection method was used for micromachining after a constant voltage or pulse energy mode has been set up. The laser projection method uses shots falling in one place through a photomask. The working parameters of the laser machine for the ablation of the SU-8 photoresist layer were a shot number, laser fluence, and pulse repetition rate ranging from 5 to 80 shots, 0.2 to 0.8 J/cm^2, and 1 to 100 Hz, respectively. The relationship between these parameters can be expressed as

$$f = \frac{S}{H/V} \tag{1}$$

where f is the repetition rate, S is the laser shot number, H is the dimension of the mask pattern in the scanning direction (in micrometers), and V is the workstation scanning velocity (in millimeters per minute).

As can be seen from the aforementioned expression, although there are many laser variables, such as V, S, and f, only two are independent. Equation (1) can be rearranged as

$$H = \frac{SV}{f}. \tag{2}$$

Equation (2) reveals that H is proportional to S, and when a larger H is exposed to the laser beam energy, a deeper workpiece ablation thickness will be achieved. Based on the aforementioned theory, different mask patterns can be designed to obtain various values of H. The laser energy profile for the mask pattern in terms of the laser shot number [see (2)] can be calculated, with which a 3-D microstructure can be analogously predicted

$$D = KS \tag{3}$$

where D is the ablation depth in the substrate and K is the coefficient of the thermal and photochemical properties of the workpiece, such as the molecular bond energy, molecular weight, and optical absorption coefficient.

However, the substrate thermal and photochemical properties are difficult to evaluate and play an important role in laser ablation. Thus, the depth is a function of S and K, where K can be treated as a calibration number and is a function of the material's thermal and photochemical properties. Based on (2) and (3), as long as the mask pattern is defined, the lithography of a 3-D structure nozzle plate produced using laser ablation can be predicted.

Fig. 1(a) shows the relationship between the fluence and the ablation rate. The pulse frequency and the pulse number are 20 Hz and 50 shots, respectively. The experiment result is that the greater the fluence, the higher the ablation rate. Fig. 1(b) shows the influence of pulse frequency on the ablation rate; the fluence and pulse number are fixed at 0.455 J/cm^2 and 50 shots, respectively. When the frequency is higher than 10 Hz, there is no apparent change in the ablation rate. Fig. 1(c) shows the relationship between the pulse number and the ablation rate; the pulse frequency and fluence are 20 Hz and 0.455 J/cm^2, respectively. The ratio of the pulse number to the depth of the SU-8 thin film can be found, as shown in Fig. 1(c). From the experimental data, it can be seen that a high pulse energy increases the ablation rate but that too much energy destroys the Cr film on the photomask. Increasing the pulse frequency and fluence increases the velocity of the workpiece scan and decreases the entire machining time; however, too high a frequency and energy will increase the effect of cumulative heat, and thus, thermal stress will influence the quality of the machining of the SU-8 thin film. The inclined angle of the machining nozzle hole also correlates with the fluence and pulse frequency. The ablated diameter of the front and back for different laser fluences was examined, and the relationship between diameter and fluence is shown in Fig. 2. For a fluence of 0.455 J/cm^2, for example, the ablated front and back diameters were observed to be 43 and 25 μm, respectively. Hence, a conical shape is created in the kerf. When the laser beam is directed onto the SU-8 thin film, first, the incident energy is absorbed on the front side during the ablation process; then, the energy is absorbed

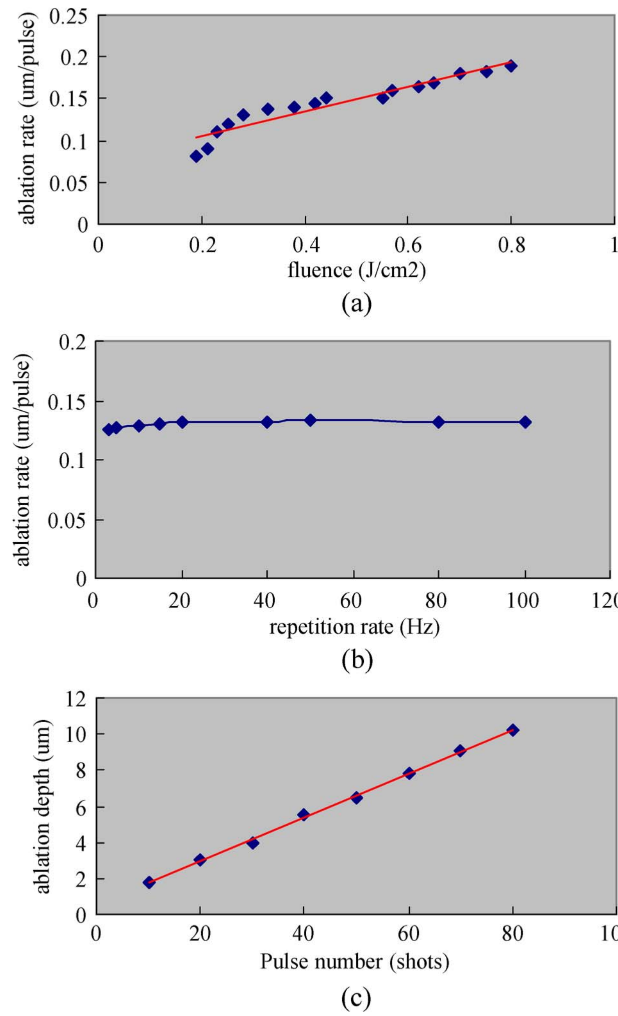

Fig. 1. Process of SU-8 substrate with excimer laser ablation. (a) Relationship between fluence and ablation rate (20 Hz, 50 shots). (b) Influence of pulse frequency on ablation rate (50 shots, 0.455 J/cm^2). (c) Relationship between pulse number and ablation rate (20 Hz, 0.455 J/cm^2).

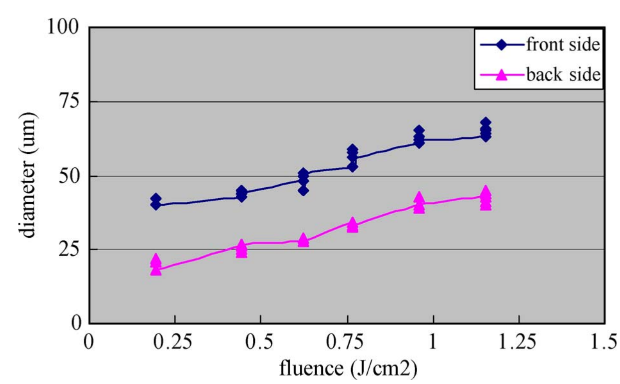

Fig. 2. Relationship between diameter and fluence for ablation diameter of front and back sides (10 Hz).

for material removal, and this behavior explains why a nozzle conical in shape is created. It makes sense that the larger the fluence, the larger the diameter. The original nozzle dimension on the mask was 25 μm in diameter. When the fluence was 1.152 J/cm^2, as shown in Fig. 2, a front diameter of 65 μm was observed. From the results, it can be seen that the ablated diameters depend significantly on the laser fluence. The conical

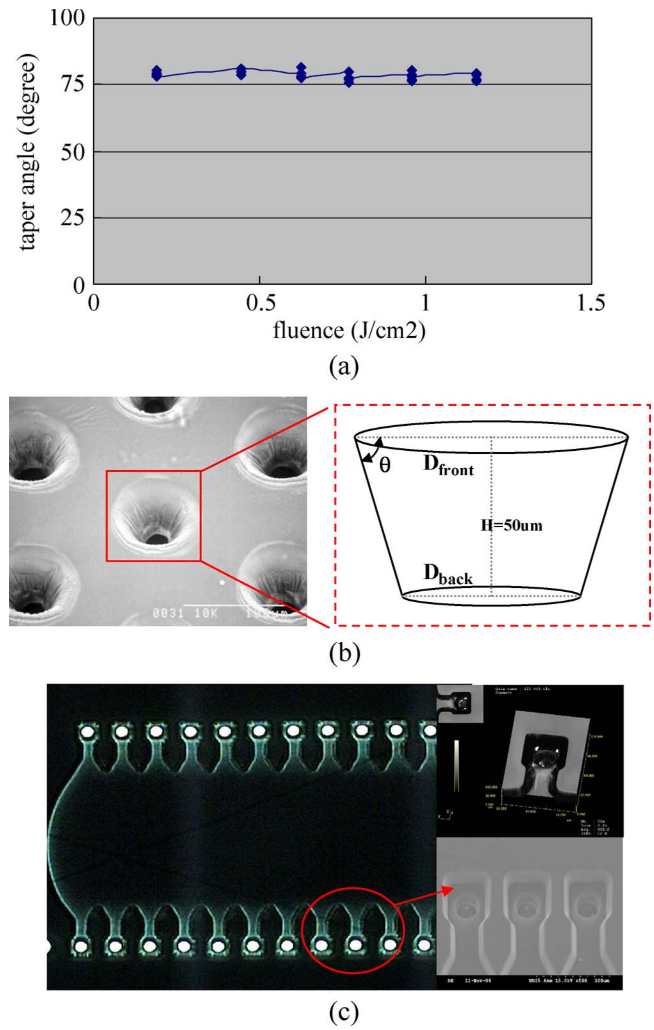

Fig. 3. Lithography process of 3-D structure nozzle plate, with taper angle, was achieved by excimer laser. (a) Conical nozzles produced at different laser fluences. (20 Hz). (b) Diameter of the front and back sides and the taper angle, D_{front}, D_{back}, θ, and experimental results, respectively, 0.455 J/cm^2, 20 Hz, and 680 pulses. (c) Experimental results of 3-D nozzle plate structure before electroforming.

nozzles produced at different laser fluences were calculated, as shown in Fig. 3(a). The taper angle ranged from 9° to 11° to vertical $(H = 50\ \mu\mathrm{m})$, as shown in Fig. 3(b), which reveals that although the diameter is influenced significantly by laser fluence, the taper angle is less dependent on it. When a smaller value of laser fluence was applied, a smaller front and back diameter was observed; on the other hand, when a greater fluence was applied, an obvious through hole resulted, leading to larger front and back diameters. During the laser ablation experiments, different diameters in the front and back of the SU-8 thin film were observed in the ablation process at different laser fluences.

Therefore, based on the results of this paper, suitable processing parameters of a pulse frequency of 20 Hz and a fluence of 0.455 J/cm^2 were selected. As shown in Fig. 1(c), a pulse number of approximately 640 shots must be used when machining an 80-μm-thick film. In order to ensure completeness of machining, we used 680 shots as the machining parameter for a microcore pin of a conical shape. The lithography process of a 3-D structure nozzle plate with a tapered angle was achieved by excimer laser. In Fig. 3(b), the diameters of the front and back and the taper angle, which are represented, respectively, by D_{front}, D_{back}, and θ; H; and the experimental results are shown. The values of 0.455 J/cm^2, 20 Hz, and 680 pulses, as well as the results shown in Fig. 3(c), were used in the fabrication of the microstructure of a micro nozzle plate by excimer laser, and an Olympus OLS3000 laser confocal microscope was used to measure the structure and the depth of the diameter.

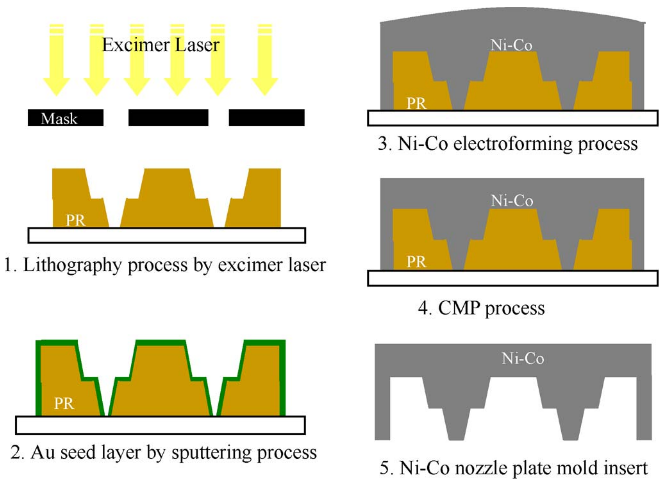

Fig. 4. Fabrication process of the 3-D structure nozzle plate mold insert.

TABLE II
Ni–Co Alloy Electrolyte Composition and Operating Conditions

Parameter	Condition
Ni concentration	75g/L
Co concentration	1-25%(w/o) in sol.
Boric acid	35-50g/L
Current density	1-10ASD(Adm-1)
pH	4.0±0.5
Temperature	60±1 °C
Agitation	Magnetic stirrer

B. Fabrication of the 3-D Structure Nozzle Plate Mold Insert

The micromold insert was in the range submicrometer to 1 nm in size, and the dimension precision was within 1–10 μm. Lithography process technology is used in the fabrication of the traditional nozzle plate mold inserts to pattern the microcore pin and microchannel; microelectroforming technology is then used to fabricate the mold insert. However, spin-coating the photoresist onto the multilayer microstructure always causes the surface of the microstructure to become lacunose; when the substrate is soft baked with the thermal plate, the thermal air flows upward through the gaps in the microstructure and breaches the photoresist layer, generating air bubbles. Therefore, it is necessary to avoid the surface of the mold insert and multilayer influences affecting the smoothness of the spin-coating of the SU-8 photoresist. This paper therefore used a 248-nm excimer laser lithography technology to improve

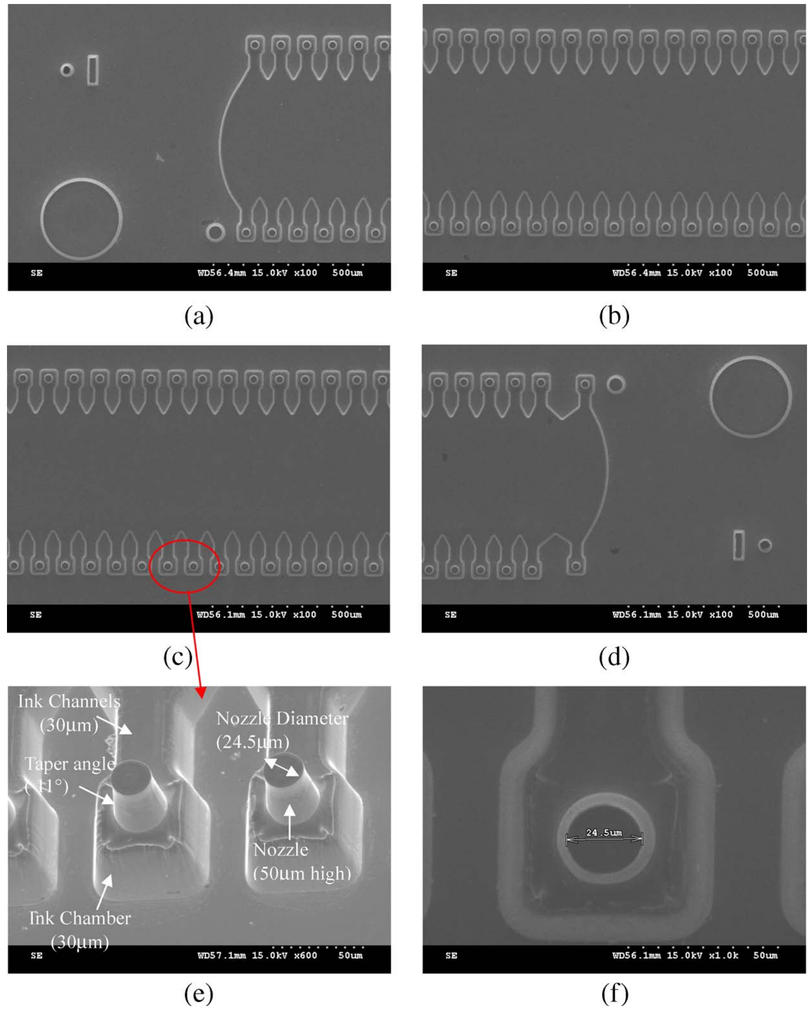

Fig. 5. Panorama of the mold insert of the micro nozzle plate with 1200 dpi.

these problems; it also overcame the problem of lithographic technology (such as the photolithography process, reactive ion etch (RIE) deep-etching process, and so on) being unable to be used to fabricate conical structures. At present, the nozzle holes of inkjet nozzle plates are designed using a taper angle, which has the advantage of reducing the generation of satellite drop when the ink jets out. Nozzle holes with a conical angle can be fabricated by adjusting the processing fluence of the excimer laser system. The design requirements of the 3-D structure nozzle plate are shown in Step 1 of Fig. 4; Steps 2–4 of Fig. 4 show the fabrication process, from the sputtering of the Au seed layer to the electroforming of the Ni–Co mold insert. The mold insert requires an electroformed layer of low stress and high hardness, as well as inside microholes of homogeneous fluence during the electroforming process. Thus, the electroforming began at 0.5 amps per square decimeter (ASD), and after 60–70 min, the fluence was adjusted to 1 ASD until the micromold insert was completed. For the Ni–Co electroforming, when 0.5% of stress-reducing agents were added and the current density was controlled appropriately, the internal stress could be reduced to zero. The Ni–Co alloy electrolyte compositions and operating conditions used are listed in Table II. Chemical mechanical polishing (CMP) technology was then used to polish the rear side of the mold insert. Both the parallelism and flatness of the micromold insert were less than 2 μm, rendering it suitable for the sequential accurate fabrication of the mold. The substrate was then immerged in the stripper to peel off the substrate and micromold insert by liftoff technology and was then cleaned by deionized water. Step 5 of Fig. 4 shows the mold insert and substrate liftoff process schematically. A roughness of the Ni/Co micromold insert rear surface of $Ra \leq 0.5\ \mu\text{m}/10\ \mu\text{m}$, and an HV value representing a hardness of about 550 was applied in the development of the microinjection mold. Fig. 5(a)–(d) shows a panorama of the mold insert of the micro nozzle plate with 1200 dpi. Fig. 5(a) and (d) shows the left and right ends of the 3-D micro nozzle plate, respectively, and Fig. 5(b) and (c) shows the middle part of the 3-D micro nozzle plate. The large assembly holes (250 μm in diameter) at the left lower corner of Fig. 5(a) and the right upper corner of Fig. 5(d) are the positions for the assembly of the nozzle plate onto the printhead. At the ends of each row of nozzle holes close to the assembly holes are two alignment holes (50 μm in diameter). Fig. 5(a)–(d) also shows the design of the ink channels; the ink supply from the cartridge runs through the main ink channel into the branch ink channels. After reaching the ink chamber, as shown in Fig. 5(e), the ink is ready for injection, which begins with heating by the heating chip. Fig. 5(e) and (f) shows that the diameter of the tapered

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